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Dr. Robert P. Bryson
Lunar Programs Office
Code SM
NASA Headquarters
Washington, D.C. 20546

Dear Bob,

Transmitted herewith are three copies of the semi-annual report for grant NGL 05-007-002, plus preprints of four papers wholly or partly supported thereby.

Thanks for your letter of January 31, 1975. The one remark which I might take exception to is "...some good university scientists...can spend relatively little time on our individual lunar grant". Please judge by the quality of results as averaged over a few years, and ask your referees to do so. While your grant has received more than its share of our attention in the past year, it is true there are ups & downs. The important thing is the quality of effort. For example, a day's effort by Jerry Schubert on lunar convective processes is worth more than thirty days by most people whom a NASA center could get for this task.

Yours sincerely,

Bill

William M. Kaula

WMK/erl

Encl. 3 xc:
Semi-Annual Report
"Early Scattering by Jupiter..." (Kaula & Bigeleisen)
"Dynamics of Lunar Origin..." (Kaula & Harris)
"...Gravity and Shape of the Moon" (Kaula)
"The Seven Ages of a Planet" (Kaula)

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DEPARTMENT OF PLANETARY AND SPACE SCIENCE
LOS ANGELES, CALIFORNIA 90024

SEMI-ANNUAL REPORT FOR GRANT NGL 05-007-002

For the Period July 1-December 31, 1974

ANALYSIS OF LUNAR EVOLUTION, WITH EMPHASIS ON DIFFERENTIATION AND DYNAMICS

Principal Investigator: W. M. Kaula

Dynamics of Lunar and Satellite Formation

A. W. Harris, W. M. Kaula

The study of binary accretion models of earth and moon formation was largely completed. In these models, the earth and moon form in orbit about each other from infalling planetesimals. The growth in mass of the two bodies draws them together, while tidal friction and gain of angular momentum drives them apart. The principal results of the study are:

1. The balance between energy brought into a circumterrestrial ring by bombardment by planetesimals and energy loss by internal collisions sustained a proto-lunar ring in a gravitationally stable configuration until its mass reached $\sim 10^{-4}$ of the earth's mass. When the mass of the ring exceeded this value it was gravitationally unstable and coagulated rapidly into a few moonlets.

2. For values of Q expected for the solid earth, a newly coagulated lunar embryo would have been held at ~10 planet radii by the opposing forces of tidal friction and accretion drag. Such an embryo, formed early in the planet's growth at $\sim 10^{-4}$ of the planet's mass, would have become relatively much more massive in the course of the remaining growth. If accretion is limited to direct accretion onto the moon, it would have had to begin growing when the earth was only 1/10 its final size, and would have gained most of its mass by the time the earth was half-formed.

3. However, if there were further collisions by planetesimals in the vicinity of the earth leading to geocentric orbits beyond the proto-moon, then the effective lunar cross-section may have been increased sufficiently that the moon's growth was predominantly later.

4. The earth's primordial rotation rate of 1 rev./5 hrs. was used to estimate the amount of angular momentum added to the proto-moon by planetesimal infall. It was concluded that this effect was minor compared to tidal friction in moving the proto-moon outward.

The aforedescribed study was incorporated in the Ph.D. dissertation of A. W. Harris, together with other work explaining the different evolutions of other planet-satellite systems.

In addition, a critical examination was made of all theories of lunar origin developed since 1970, in view of the new constraints generated by the Apollo project. The results of this examination have been incorporated in an article in Reviews of Geophysics & Space Physics (preprint enclosed).

The principal work pertaining to the purely dynamical aspects of lunar origin which remains is to develop better estimates of the relative probabilities of planetesimal-planetesimal, planetesimal-proto-moon, and planetesimal-proto-earth collisions as functions of planetesimal size and orbit. Such probabilities depend of course on nebula models. They affect the time of lunar formation, mentioned in 3. above, the differentiation mechanisms discussed below, and the possibility of capture of larger bodies as hypothesized by others.

Mechanical Processes Affecting Differentiation of Proto-Lunar Material

W. M. Kaula, P. E. Bigeleisen

Detailed examination was given to the hypotheses that scattering of planetesimals by Jupiter resulted in significant energy inputs to the terrestrial zone, and that the differences in capture probability of the proto-earth and the proto-lunar swarm lead to significant differences in composition. This examination utilized mainly Monte Carlo computations to estimate the effects of several parameters. Work so far is conveniently described in two phases: the first, considering only the physical effects, directed mainly to estimate the differences in fragment size, heating by collisions, etc. of proto-lunar and proto-earth material; the second, taking into account compositional differentiation in planetesimals.

The first phase comprises five stages: (1) velocity dispersion at Jupiter's orbit, treating the mean square velocity from Safronov's theory as the parameter of a Maxwell distribution isotropic at Jupiter's orbit; (2) energy and mass transfer to other zones, by converting position and velocities at Jupiter's orbit to a Kepler orbits about the sun and assuming number density to have an exponential dependence on mass for each Monte Carlo case; (3) collision frequency in the earth zone, estimating the frequency with which an earth zone planetesimal would encounter a Jupiter scattered planetesimal above a specified size; (4) collision modeling: for each Jupiter zone-earth zone planetesimal collision, the partition of energy into heat, comminution, & recoil kinetic energy, and the size distribution of resulting fragments; and (5) relative properties of proto-earth and proto-lunar matter, from the differing capture probabilities of proto-earth and proto-moon for collision fragments.

The principal inferences from this work are: (1) if Jupiter attained 3% or more of its final mass before the earth-moon system had completely formed, then there were significant collision effects from scattered planetesimals in the earth zone; and (2) if a significant earth embryo had formed (say, 10% of the final mass or more), then the differences in heating and fragment size of proto-earth and proto-lunar material would have been drastic. This phase of the work will soon be published in Icarus (preprint enclosed).

The second phase assumes four compositional components--iron, ferromagnesian silicates, calc-aluminous silicates, and ice--of planetesimals. Allowance is made for the differing temperature dependence of melting and vaporization of these components, for varying degrees of planetesimal differentiation, and for correlation of fragment size with location within a fractured planetesimal. If these elements are added to the first phase Monte Carlo calculations, then to attain the lunar enrichment in refractory silicates and depletion in iron the planetesimals prior to collision must already be 80% or more differentiated. Consideration is now being given to multiple collisions, as was probable, as well as greater concentration of the heat energy indicated by the impact calculations described below.

Evolution of the Lunar Orbit under Tidal Friction
C. F. Yoder, W. M. Kaula

In view of the recurrent vague suggestions by Alfven, Turcotte, etc. of resonant complings delaying the outward evolution of the moon, more detailed examination is being given to such mechanisms. One which appears marginally possible arises from the commensurability between the motions of Jupiter and the moon's perigee which occurred when the moon was about 15 earth radii distant. The stability thereof depends on a somewhat larger eccentricity than now, which is difficult to reconcile with the differing dissipation characteristics of the earth and moon.

The conditions for a lock on irregularities in the earth's field are also being established more precisely. The maintenance of an eccentricity by a balance between earth and lunar tidal dissipation, as well as appreciable tesseral harmonics, is critical.

General Consideration of Lunar Evolution
W. M. Kaula

Considerable thought was given to the differences of the moon from the terrestrial planets, with a view to reconciling the lunar state with it being the most evolved in a common sequence of stages, primarily due to more rapid radiation of its heat. See enclosed preprints "The Seven Ages of a Planet" and "The Gravity and Shape of the Moon".

Early Lunar Infall History
C. F. Yoder, W. M. Kaula

Utilizing the preciously developed general theory for the secular changes of a planetary system, the spilling of planetesimals out of the gaps between the major planets was examined as a possible explanation for the lunar "cataclysm" 4 b.y. ago. Successive growth of Jupiter, Saturn, Uranus, Neptune appears necessary to account for the thoroughness with which the intervals between the planets have been cleared out. Yet to be examined are the probabilities of spilled planetesimals penetrating the Jupiter barrier. (This work was transferred Jan. 1 to grant NSG-7113).

Modelling of Impact Heating of the Outer Parts
W. M. Kaula, G. J. Ransford

This work is still at the stage of exploration discussions. One inference from the lunar formation work by A. W. Harris is that it is unlikely that moonlets which were significant fractions of the entire moon came together in circumterrestrial orbit, if the tidal friction rate was at all comparable to that at present, or that the moon was ever broken up after it became more than 10 percent its final size. Hence rapid accretion may be less important than previously thought. However, it does seem certain that during its formation the moon was hit by planetesimals appreciably larger than the Imbrium impacter from outside the earth-moon system.

More specific modeling of melting effects is awaiting completion of J. D. O'Keefe's dissertation, which now will include a numerical calculation of the Imbrium impact as well as the thermodynamic effects (see "Shock Metamorphism effects from a Basin-forming Impact on the Moon" by O'Keefe & Ahrens, Sixth Lun. Sci. Conf. Abstracts).

Modelling of Thermal Convection Associated with Differentiation of the Lunar Crust
G. Schubert

We have proposed that convective motions in the outer part of the Moon accompanying the differentiation of an anorthositic crust were important in accumulating a crust of nonuniform thickness. This could explain the nearside farside lunar crust thickness asymmetry inferred from the lunar center of mass - center of figure offset. Thus our long-term objective is to model convection in a differentiating medium.

Prior to attempting a description of such a complex mechanical-thermal-chemical system we are presently modelling the simpler situation of how convection (subsolidus) may influence the internal thermal state of the Moon. These calculations not only provide a necessary foundation for future computations which will include effects of differentiation in a convecting medium, but they are important in their own right, resulting in quantitative solid-state convection models of the temperature of the lunar interior. The calculations are being carried out using a computer program developed by R. E. Young (NASA Ames Research Center) to describe convection in a spherical shell.

We plan to investigate a number of models of the present lunar thermal state. To date, we have results for two lunar temperature models. Both are three-layer models consisting of a core, convecting mantle and rigid outer lithosphere. Radioactive heat sources are distributed uniformly throughout the mantle and lithosphere and the mantle has a constant Newtonian viscosity. Other thermal and mechanical properties such as thermal conductivity, specific heat at constant pressure, density, etc. have the same constant values in the mantle and lithosphere. The core-mantle interface is a free-insulating boundary (no heat from the core) while the mantle-lithosphere boundary is a rigid surface across which temperature and heat flux are continuous. The surface of the Moon is assumed isothermal. In both models the core is 300 km in radius. In one model the lithosphere is 300 km thick and the radioactive heat source concentration has the average value appropriate to the earth's mantle. For the other model, the heat sources are only half as strong and the lithosphere is much thicker, 800 km.

The major results of the calculations are profiles of the Moon's average temperature as a function of depth with the viscosity of the lunar mantle as a parameter. Viscosities ranging from about 6×10^{23} to 6×10^{21} poise have been considered for the model with a 300 km thick lithosphere, for example. Solid-state convection leads to relatively uniform temperatures in the mantle. By comparing the model core-mantle interface temperatures with the melting temperatures of Fe or Fe-FeS we can discuss the likelihood, from the thermal point of view, that the Moon has a small liquid metal core.

A paper describing these results is now in preparation. It is planned to present the paper at the Royal Society Discussion Meeting "The Moon, a New Appraisal from Space Missions and Laboratory Analyses", June 9-12, 1975. London and submit it to Phil. Trans. Roy. Soc. for publications.